V. *Experimental Researches in Magnetism and Electricity.* *By* H. Wilde, *Esq.* *Communicated by Dr.* Faraday.

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§ 1. *On some new and paradoxical Phenomena in Electro-magnetic Induction, and their relation to the Principle of the Conservation of Physical Force.*

§ 2. *On a new and powerful Generator of Dynamic Electricity.*

1. The principle of the conservation of force, as I apprehend it, is the definite quantitative relation existing between all the phenomena of the universe whatsoever, both in direction and amount, whether such phenomena be considered in the relation of cause and effect, or as antecedent and consequent events.

2. In the particular application of this principle to the advancement of physical science, and also to the invention of new engines and machinery to meet the progressive requirements of society, problems not unfrequently present themselves which involve the consideration of static and dynamic force, from several different aspects; and the solution of these problems often brings out results which are as surprising as they are paradoxical. Of such cases, in which the idea of paradox alluded to is involved, may be mentioned the one contained in the 36th Proposition of Newton's 'Principia' (Book 2, Cor. 2)*, and in D. Bernoulli's 'Hydrodynamica,' p. 279; in which the repulsive force of a jet of water issuing from a hole in the bottom or side of a vessel with a velocity which a body would acquire in falling freely from the surface, is equal to the weight of a column of water of which the base is equal to the section of the contracted vein and about twice the height of the column which produces the flowing pressure; the *static force* of reaction being thus double that which, without experiment, had been predicted†. An instance in which the quantity of *dynamic force* is increased paradoxically may be seen in that curious and useful piece of apparatus the injector, by means of which a boiler containing steam of high pressure is able to feed itself with water through a hole in its shell, though this hole is open to the atmosphere; or the steam from a low-pressure boiler is enabled to drive the feed-water through a hole (also open to the atmosphere) into a high-pressure boiler. Although, when rightly interpreted, these examples of paradox, as well as many others of a similar character, are in strict accordance with the principle of conservation, yet they are at the same time contrary to the inferences which are generally drawn from analogical reasonings, and to some of those maxims of science which are framed for the instruction of the unlearned. As the examples cited are only

* Principia, 2nd Edition.

† Ibid. 1st Edition, Book 2. Prop. 37.

adduced for the purpose of illustrating some analogous phenomena observed in connexion with certain combinations of static and dynamic force in molecular mechanics which form the subject of the present research, it is not my intention to enter into the rationale of either of them, but to direct attention to some new and paradoxical phenomena arising out of FARADAY'S important discovery of magneto-electric induction, the close consideration of which has resulted in the discovery of a means of producing dynamic electricity in quantities unattainable by any apparatus hitherto constructed.

3. If round a piece of iron forming the armature of a permanent magnet a quantity of insulated wire be wound at right angles to the line which joins the poles of the magnet, and if the free ends of the wire be connected together directly, or indirectly by the interposition of some conductor, a momentary wave of electricity, as is well known, is generated in the wire every time the armature is suddenly removed from the magnet, or suddenly approaches it; and the wave of electricity generated by the removal of the armature moves in the opposite direction to that generated by the approach of the armature. With a description of this simple experiment, FARADAY announced (in 1831) the discovery of magneto-electricity*, which was found to possess all the distinguishing characteristics of electricity derived from any other source.

4. The force of a permanent magnet is usually estimated by the weight which is required to separate the armature or submagnet from its poles; and if the question were asked, for the first time, what relation existed between the sustaining-power of an electro-magnet excited by means of a magneto-electric machine, and the sustaining-power of the permanent magnet from which the electricity was derived, it would probably be answered, that since the permanent magnet was the primary cause of the phenomena, the electro-magnet would possess, at the most, no greater sustaining-power than the permanent magnet. This, however, is not the case; for I have found that an indefinitely small amount of magnetism, or of dynamic electricity, is capable of inducing an indefinitely large amount of magnetism. And again, that an indefinitely small amount of dynamic electricity, or of magnetism, is capable of evolving an indefinitely large amount of dynamic electricity.

5. That FARADAY himself stood on the threshhold of this discovery, will be obvious from the following observations made by him in a paper "On the Physical Character of the Lines of Magnetic Force"†, in which, when speaking of the magnet as a source of electricity, he says, "Its analogy with the helix is wonderful, nevertheless there is, as yet, a striking experimental distinction between them; for whereas an unchangeable magnet can never raise up a piece of soft iron to a state more than equal to its own, as measured by the moving wire (3219), a helix carrying a current can develope in an iron core magnetic force, of a hundred or more times as much power as that possessed by itself, when measured by the same means. In every point of view, therefore, the magnet deserves the utmost exertions of the philosopher for the development of its nature, both as a magnet and also as a source of electricity, that we may become acquainted with the

* Philosophical Transactions, 1832, vol. cxxii.

† Philosophical Magazine, June 1852, par. 3273.

great law under which the apparent anomaly may disappear, and by which all these various phenomena presented to us shall become *one*."

6. As the investigations which led to the paradoxical conclusions enunciated above (4) were not originally intended for publication, but were undertaken for my own instruction, I find that it will be much more convenient to describe the experimental results in a more methodical manner than that in which they were obtained.

7. The numerical determinations, derived from the experiments to be described, will be given with sufficient exactitude to allow of a comparison being made between them and those of other experimentalists. Other quantitative determinations will, for the present purpose, be sufficiently expressed by the terms "greater" and "less," as attention will be chiefly confined to a description of well-defined phenomenal effects.

8. Though I make use of certain conventional terms in connexion with the subject of these researches, it is not thence to be inferred that I hold to the opinion that specific entities distinct from ordinary matter are concerned in the production of phenomena of any kind whatever.

9. The apparatus with which the experiments were made is shown in Plate VI. figs. 1–10. Two blocks of cast iron, A, A, of the form shown in figs. 1, 2, 3, and two pieces of brass, B, B, of the same length as the cast-iron blocks, were bolted together at the top and bottom with small brass bolts, in such a manner as to form a compound hollow cylinder of brass and iron, hereafter called the magnet-cylinder. A smooth and parallel hole C, $1\frac{5}{8}$ inch in diameter, was bored through the magnet-cylinder; and the thickness of the brass packings, B, B, separating the iron sides of the cylinder from one another, was three-quarters of an inch, or nearly half the diameter of the hole. Two pillars of wrought iron, D, D (fig. 3), were screwed into the cast-iron projections E, E (figs. 1, 2, 3) at each end of the magnet-cylinder, for the purpose of holding the cross-heads F, F, fig. 3. These cross-heads were made of brass, and were bored out concentrically with the hole through the magnet-cylinder, so as to form suitable bearings in which the journals of an armature might revolve.

10. The armature, which was of the same form as that used by Siemens (figs. 4, 5, 6, 7), was made of cast iron, and was turned parallel throughout its entire length, and about one-twentieth of an inch less in diameter than the hole in the magnet-cylinder, for the purpose of allowing it to revolve inside the cylinder in close proximity to it, but without touching it. The thickness of the rib G, uniting the segmental sides of the armature (figs. 4, 5, 7), was one-quarter of an inch. Two brass disks or caps, H, H′, having concentric prolongations for holding the steel journals I, I, were fitted by means of screws, one at each end of the armature. A pulley, K, for driving the armature was fixed upon the cylindrical axis of the cap H′, and upon the axis of the cap H at the other end of the armature, a commutator, L, L′, of hardened steel was fixed.

11. About 163 feet of copper wire 0·03 of an inch in diameter, insulated with silk, was wound upon the armature (fig. 6) in the direction of its length. The inner extremity of the wire was placed in good metallic contact with the armature, and its outer

extremity was connected with the insulated half L′ of the commutator by means of a clip and binding screw. Bands, encircling the armature at intervals, and sunk below the surface of the iron in grooves turned out for their reception, prevented the convolutions of insulated wire from flying out of position by the centrifugal force attending their rapid revolution. The armature is represented complete in fig. 6, and in section in fig. 7.

12. A number of exactly similar permanent magnets (of the form shown in fig. 1), 8 inches long, were made from bars of steel 1 inch wide and a quarter of an inch thick, and the distance between the inner edges of the polar extremities of the magnets was a little less than 2 inches. The magnets weighed about one pound each, and they received very nearly equal degrees of magnetism, which enabled them to support a weight of about ten pounds each.

13. On each side of the magnet-cylinder was a flat raised surface, M, M, figs. 2, 3, extending the whole length of the cylinder between the projections E, E. These surfaces were planed parallel with each other and with the axis of the magnet-cylinder. When the magnets, the legs of which were somewhat less than 2 inches apart, were sprung upon the cylinder in the position shown in fig. 1, they were held in sufficiently good contact for the magnetism to diffuse itself equally throughout the entire mass of the cylinder; the two cast-iron sides of which, consequently, formed the poles of the magnets. On the lower part of the magnet-cylinder four projections or feet, N, N, N, N, figs. 2, 3, were cast, by means of which it was bolted firmly to a wooden base.

14. When the armature was made to revolve rapidly in the interior of the magnet-cylinder, waves of magneto-electricity were generated in the coils by the reversals of the magnetism in the rib G; and from the peculiar construction of the cylinder and armature, two waves of electricity, moving in alternate directions, were generated for each revolution of the armature.

15. The rapid succession of alternating waves thus generated could be taken from the machine as an intermittent current moving in one direction, by means of two steel springs (shown in the perspective drawing, fig. 10), when they were made to rub against the opposite sides of the commutator L.

16. The waves of electricity could also be taken in alternate directions from the machine when required, by adjusting the springs so as to rub against the unbroken cylindrical part of each half of the commutator.

17. The springs were placed in metallic connexion with the respective polar terminals of the machine, and to these terminals wires were attached for making the necessary connexions with those of a galvanometer or of an electro-magnet.

18. The first series of experiments with the magneto-electric machine thus described, was made for the purpose of ascertaining what influence the number of magnets on the cylinder had upon the quantity of electricity generated by the machine, as indicated by the galvanometer.

19. During these investigations, the armature of this machine was driven by steam-power at a constant velocity of three thousand revolutions (equivalent to six thousand

waves of electricity) (14) per minute. The direct current from the machine (15) was transmitted through one of POUILLET'S galvanometers of tangents, constructed by RUHMKORFF, which was placed beyond the influence of the magnetism of the machine. The resistance of the galvanometer coils was so small in proportion to the resistances of the other circuits employed in these researches, as to render it unnecessary to take it into account.

20. Four permanent magnets (12) were placed successively upon the magnet-cylinder at a distance of half an inch from one another, and as each additional magnet was placed upon the cylinder, the deviation of the galvanometer-needle was read off after it had taken up a steady position. The results of these experiments are shown in the following Table.

TABLE I.

No. of magnets on cylinder.	Deviations of galvanometer.	Tangents of deviations.
1	29°·25	0·56
2	52·00	1·28
3	62·75	1·94
4	67·75	2·44

21. In making these experiments, which have often been repeated at different times, it was invariably found that, when only one magnet was on the cylinder, the quantity of electricity generated by the machine was proportionately less than when two or more magnets were placed on the cylinder. This deficiency appears to me to be due to the small amount of magnetism of a single magnet having to diffuse its influence through the comparatively large masses of iron of which the cylinder and armature were composed. After making allowance for this discrepancy, together with errors of observation, it will be seen from an inspection of the above Table, that, within the limits of these experiments, the quantity of electricity generated in the wire surrounding the armature of the magneto-electric machine is in direct proportion to the number of magnets on the magnet-cylinder, or to the quantity of magnetism induced in it.

22. A second series of experiments was made with the view of ascertaining the relation existing between the lifting-power of the permanent magnets on the magnet-cylinder, and that of an electro-magnet excited by the electricity derived from the magneto-electric machine. In these investigations the apparatus shown in fig. 8 was used, which consisted of a small electro-magnet, made by bolting to an iron block, forming the base of the electro-magnet, two plates of iron 6 inches long, 3 inches wide, and $\frac{5}{8}$ths of an inch thick. The inside distance between the two plates was about 2 inches; and the polar surfaces of the magnet were truly planed, as was also the under surface of the keeper or submagnet used in connexion with it. This submagnet was made of a small block of iron about 3 inches square and 1 inch in thickness, and was connected, by means of a link and swivel, to one end of a scale-beam supported at its centre by an upright pillar. From the other end of the beam depended a scale-pan, which was weighted so as to

exactly counterbalance the weight of the submagnet. The stand supporting the scale-beam was firmly bolted to an iron lathe-bed, as was also the electro-magnet, which was placed in a vertical position beneath the submagnet.

23. Around each side or plate of the electro-magnet, a length of 100 feet of insulated copper wire 0·05 of an inch in diameter was coiled, and the ends of the wires were so arranged that they could, at pleasure, be coupled up so as to form a single circuit of 200 feet, or a double circuit of 100 feet in length. One foot of the wire on the armature of the magneto-electric machine had a resistance equal to 3 feet of the single wire on the electro-magnet.

24. Experiments were made, in the first instance, for the purpose of ascertaining what influence the number of magnets on the magnet-cylinder had upon the attractive force mutually exerted by the electro-magnet and the submagnet. As the scale-beam was of too delicate a construction to allow of the submagnet being placed in direct metallic contact with the electro-magnet, a piece of thin cardboard was fastened upon the poles, by means of gum. The wires of the electro-magnet were coupled up so as to form a double circuit 100 feet in length, the resistance of which was about one-tenth of the resistance of the armature circuit. The electro-magnet was excited by the direct current from the magneto-electric machine. The submagnet was then placed upon the covered poles of the electro-magnet, and small weights were introduced into the scale-pan of the balance until the submagnet was separated from the electro-magnet.

25. In order that a more rigid comparison might be made between the quantities of electricity derived from the magneto-electric machine and the amount of the attractive force mutually exerted by the electro-magnet and the submagnet, the particular experiments, the results of which are given in Tables I. and II., were made simultaneously, the tangent galvanometer at the same time forming part of the same metallic circuit as the electro-helices and the wire surrounding the armature.

26. Coordinate results, such as are shown in Tables I. and II., were, however, obtained, whether the first and second series of experiments were made either together or separately.

TABLE II.

No. of magnets on cylinder.	Weight, in ounces, required to separate submagnet from electro-magnet.	Squares of magnetic force of the magnet-cylinder.
1	2·50	2·50
2	11·25	10·00
3	24·00	22·50
4	38·00	40·00

27. The results arrived at, as shown in the above Table, are somewhat remarkable, and have amongst themselves a well-defined ratio, such as would hardly have been expected from a bare consideration of the nature of the magnetism of the permanent magnet; for when one magnet was placed on the cylinder, the weight required to separate the submagnet from the electro-magnet was 2·5 ozs. It might therefore have been

expected that two magnets placed on the cylinder would have induced a double amount of magnetic force in the electro-magnet, whereas the force required to detach the submagnet was equal to a weight of 11·25 ozs., or was a little more than quadrupled. From a further comparison of the numbers contained in the Table, it will be seen that (within the limits and conditions of these experiments, and after making allowance for a certain degree of imperfection in them) the amount of magnetism induced in the electro-magnet, as measured by the weight required to separate the submagnet, is as the square of the inducing magnetism of the permanent magnets of the electro-magnetic machine.

28. Experiments were then made for the purpose of ascertaining to what extent an alteration in the length and section of the wires surrounding the electro-magnet would influence the quantity of magnetism induced in it. The electro-helices were therefore coupled up so as to form a single circuit 200 feet in length (23), and its resistance was about four-tenths of that of the wire surrounding the armature. The experiments were conducted in the same order as those in the preceding series, the thin cardboard being still interposed between the submagnet and the electro-magnet (24), and the following Table contains the results obtained.

TABLE III.

No. of magnets on cylinder.	Weight, in ounces, required to separate submagnet from electro-magnet.	Squares of magnetic force of magnet-cylinder.
1	5·00	5
2	28·00	20
3	76·00	45
4	144·00	80

29. From a comparison of the numbers in this Table with those in Table II., it will be seen that the ratio of increase, as well as the amount of the magnetism induced in the electro-magnet, has been considerably augmented by an increase in the length of the electro-magnetic circuit.

30. Experiments were also made with the submagnet in direct contact with the electro-magnet without the interposition of the cardboard, the arrangement of the electro-helices remaining the same as in the preceding experiments (28). The small scale-beam and stand were removed from the lathe-bed, and were replaced by a stronger apparatus of a similar construction. The results of these experiments are shown in the following Table.

TABLE IV.

No. of magnets on cylinder.	Weight, in pounds, required to separate submagnet from electro-magnet.	Squares of magnetic force of magnet-cylinder.
1	31·50	31·50
2	98·00	126·00
3	150·50	283·50
4	178·50	504·00

31. From an examination of the results of these experiments, it will be seen that when the submagnet was in direct contact with the electro-magnet, the force required to separate them was very greatly increased; but the ratio of this increase, as measured by the same means as in the former experiments (22), is very considerably diminished; for when one magnet was placed on the cylinder, the addition of a second magnet increased the sustaining-power of the electro-magnet by 66·5 lbs., whereas when three magnets were placed on the cylinder, the addition of a fourth magnet was only attended by an increase of 28 lbs. in its sustaining-power.

32. But the most extraordinary fact brought out in connexion with the latter series of experiments, is the development of a much greater amount of magnetism in the electro-magnet than that which existed in the permanent magnets employed in exciting it; for while the four permanent magnets on the cylinder were only capable, collectively, of sustaining a weight of about 40 lbs., the electro-magnet, as will be seen from the Table, would sustain a weight of 178·5 lbs.

33. In order that this remarkable property might be exhibited in a more striking manner, a large electro-magnet was constructed by screwing into a heavy iron block, 6 inches in thickness, two cylinders of wrought iron 24 inches in length and $3\frac{1}{2}$ inches in diameter. Round each of these cylinders an insulated strand of copper wires, each 950 feet in length and 0·15 of an inch in diameter, was wound from end to end of the cylinders in several concentric layers, and the two electro-helices were coupled up so as to form one continuous helix 1900 feet in length. The cylindrical poles of the electro-magnet were $8\frac{1}{2}$ inches distant from centre to centre, and were furnished with a suitable submagnet, which was connected by means of a link with a strong lever, for the purpose of measuring the amount of force necessary to separate the submagnet from the electro-magnet.

34. When the four permanent magnets (20) were placed on the cylinder of the magneto-electric machine, and the electricity from it was transmitted through the electro-magnetic helices, a weight of not less than 1088 lbs. was required to overcome the attractive force of the electro-magnet, or twenty-seven times the weight which the four permanent magnets used in exciting it were collectively able to sustain. It will, however, be shown hereafter (77) that this difference between the sustaining-power of a permanent magnet and that of an electro-magnet excited through its agency, great as it is, is very far from reaching the limits to which it can be carried.

35. The question now arose, how the results obtained from these experiments were to be reconciled with the principle of the conservation of force, since it is now generally held by physicists that the calorific, magnetic, and other properties of the electric circuit are correlated, both in direction and amount; and to admit the coexistence of any one of these properties along with the others in a greater or less degree, under like conditions, would involve the idea of the miraculous or the paradoxical.

36. In experimenting with the magneto-electric machine, it was found that the dead point of the armature, or that position during its revolution in which no electricity is

evolved, varied with the length or the resistance of the wires which joined the poles of the machine. It therefore became necessary to change the position of the commutator on the armature axis, to suit the different circuits through which the electricity was transmitted, so that the burning effects of the spark at the junction of the two halves of the commutator might be avoided when the direction of the current was changed.

37. When the commutator was properly adjusted to the resistance of the wires surrounding the electro-magnet (33), I observed that so long as the magneto-electric machine was allowed to run without its poles being connected, either with the wires of the electro-magnet or any other conductor, a brilliant star of light appeared at the points where the springs were in contact with the commutator (15); but when the poles of the machine were connected by means of a short piece of wire, the bright light at the commutator instantly disappeared. It was also observed that when the poles of the machine were connected with the long helices of the large electro-magnet, a perceptible interval of time elapsed before the light at the commutator disappeared. Besides this, it was also observed that, at the moment of breaking contact between the wires of the electro-magnet and the poles of the machine, a much more brilliant spark appeared at the points of separation, and a much more severe shock was felt when the body formed part of the circuit, than could be produced by the direct action of the machine alone. The latter effects could not, however, be obtained until a certain interval of time had elapsed after contact had been made between the electro-helices and the wires of the machine.

38. Moreover, I found that a spark could be obtained from the wires surrounding the electro-magnet even after they had been entirely disconnected from the machine. This curious result was obtained by first holding the free extremities of the wires surrounding the electro-magnet, one in each hand, in contact for a few seconds with the respective polar terminals of the machine, and while contact was still maintained, bringing the ends of the electro-helices into metallic contact with each other, so that they formed a continuous metallic loop or closed circuit. The loop so formed was then suddenly removed from the polar terminals, and while thus entirely disconnected from them, the ends of the loop were suddenly separated, and a bright spark appeared at the point of disjunction. With a larger and more powerful electro-magnet (67, 68), a bright spark was in like manner obtained, twenty-five seconds after all connexion with the magneto-electric machine had been broken*.

39. None of the effects described, such as the great sustaining-power of the electro-magnet above that of the permanent magnets (34), the increased brilliancy of the spark at the point of disjunction of the wires (37), or the spark from the electro-helices after all connexion with the magneto-electric machine had been broken (38), were observed when the alternating current from the machine (16) was transmitted through the electro-helices, instead of the direct current from the commutator (15). Under these conditions

* Since this paper was read I have discovered that Dr. Page, in 1851, succeeded in obtaining a spark from an electro-magnet, coiled with a very long wire, half a second after all connexion with the battery had been broken.—Silliman's American Journal of Science, vol. xi. p. 88.

it was found that neither the small electro-magnet (22, 23) nor the large electro-magnet (33) would sustain even a weight of 1 lb.

40. It was at first thought that the great difference observed between the sustaining-power of the electro-magnet and that of the permanent magnets which excited it, might be due to the helices surrounding the electro-magnet absorbing or retaining the electricity transmitted through them in a static condition, in the manner observed in insulated submarine and subterranean telegraph wires; an investigation of which phenomenon, as it was manifested in gutta-percha-covered wires submerged in a canal, and in similar wires laid underground between London and Manchester, was made by FARADAY in 1853*.

41. For the purpose of ascertaining whether this view of the subject was correct, a very small and delicate electro-magnetic balance was constructed, similar in principle to the one shown in fig. 8. The small electro-magnet, fixed beneath one end of the balance, was coiled with a strand of insulated copper wires 6 feet in length and 0·15 of an inch in diameter. The submagnet was prevented from coming into contact with the poles of the electro-magnet by means of regulating-screws. Other regulating-screws limited the movements of the balance in the opposite direction; and the distance of the submagnet from the electro-magnet could also be adjusted, by means of the same regulating-screws, to suit the different quantities of electricity transmitted through the electro-helices.

42. This electro-magnetic balance was placed in the middle of the circuit of the electro-magnet (33), *i. e.* at the point where the two electro-helices were joined together. The poles of the magneto-electric machine were then connected with the free extremities of the electro-helices for a few seconds; and after the spark from the commutator had disappeared, the submagnet was so counterpoised, by means of small weights, as to respond immediately to the attractive force of the small electro-magnet placed beneath it, so long as the electricity from the machine was transmitted through the helices of the large electro-magnet; but when contact with the machine and the electro-helices was broken, it was observed that the submagnet was instantly withdrawn from the poles of its electro-magnet by the weights placed in the scale-pan at the opposite end of the balance.

43. The apparatus being thus arranged, it would follow that if the charge in the wire surrounding the electro-magnet were identical with that which is observed in insulated submarine-telegraph cables, a certain interval of time would elapse, after contact with the magneto-electric machine had been made, before the balance in the middle of the circuit would respond to the attractive force of the small electro-magnet placed beneath it. On making the experiment it was found that when contact was made with the machine, 1·5 second elapsed before the balance responded to the attractive force.

44. When placed in the middle of the circuit of a larger and more powerful electro-magnet (67, 68), excited by the same magneto-electric machine (18), the electro-magnetic balance did not respond to the attractive force until an interval of 15 seconds had elapsed.

* Proceedings of the Royal Institution, Jan. 20th, 1854.

45. But if the retardation of the current, as indicated by the balance when placed in the middle of the circuit, had been the effect of an accumulation of static electricity in the electro-helices, it would also have been instantly attended by a rush of the full current of electricity into the helices at the beginning of the circuit, such as was observed in the before-mentioned experiments made by FARADAY (40). On making the experiment this was not, however, found to be the case; for when the balance was removed from the middle and placed at the beginning of the electro-magnetic circuit, the wires being again joined up so as to form a continuous helix as before (33), it was still found that 1·5 second, and with the large electro-magnet (67, 68) 15 seconds, elapsed before the electricity acquired sufficient power to bring down the submagnet of the balance.

46. When the large electro-magnet (67, 68) was excited by the electricity from a larger and more powerful machine (63), driven at a velocity of 2000 revolutions (equivalent to 4000 waves) per minute, instead of that from the small magneto-electric machine, which produced 6000 waves per minute, an interval of only four seconds elapsed before the balance responded to the attractive force of its electro-magnet.

47. Moreover, the direction of the current in the electro-helices, as shown by the galvanometer, was the same *after* as it was *before* connexion with the electromotor was broken; whereas had the current, as shown by the spark obtained (38), been the result of a static charge of the kind observed in insulated telegraph wires, the electricity would have discharged itself, when the place of disjunction was at the electromotor, in the opposite direction to that in which it entered the electro-helices.

48. The conclusions drawn from a consideration of these experiments are therefore opposed to the supposition that the effects described are the consequence of a static charge of the kind observed to be retained by insulated submarine and subterranean telegraph wires; but some of the phenomena described,—such as the retardation of the current when contact was made with the magneto-electric machine (43, 45), and the exalted electrical condition of the wire surrounding the electro-magnet, as shown by the voluminous spark seen and the severe shock felt when contact with the machine was broken (37),—are identical with the phenomena of electric induction observed by Dr. HENRY* and investigated by FARADAY with the aid of the voltaic battery, and which form the subject of his Ninth Series of Researches in Electricity†.

49. That an electro-magnet possesses the power of retaining a charge of electricity in a manner analogous to that in which it is retained in insulated submarine cables and in the Leyden jar, but not identical with it, is evident from the appearance of a spark at the point of disjunction of the wires a considerable time after all connexion with the electromotor has been cut off. The production of this spark appears to me to arise from the comparatively slow manner in which large masses of iron return to their normal condition after having attained a highly exalted degree of magnetism; the rate of decrease, however, being sufficiently rapid to allow the induction-current to manifest

* SILLIMAN'S American Journal of Science, 1832, vol. xxii. p. 408.

† Philosophical Transactions, 1835, vol. cxxv.

itself in the electro-helices, with a decreasing intensity, simultaneously with the decreasing flux of magnetism in the iron itself.

50. It is this important retentive property of the electro-magnet which maintains its attractive force unimpaired, notwithstanding the intermittent character of the electricity transmitted through the electro-helices; for, as is well known, no current whatever is produced from the armature of the magneto-electric machine when in certain positions during its revolution. These positions correspond, in some measure, with the dead points of the crank of a steam-engine, the fly-wheel of which performs the same function *dynamically*, as that which the electro-magnet performs *statically*, in the case of the magneto-electric machine.

51. That the charge retained by the electro-magnet is, as has already been observed, much more powerful than that which the magneto-electric machine is of itself capable of producing, is evident from the severe shock which is felt when the body forms part of the circuit, and also from the more voluminous spark which appears at the point of disjunction of the wires when contact with the machine is broken.

52. That this increase of electric force in the electro-magnet is the consequence or effect of a certain number of electrical waves transmitted through the electro-helices, and succeeding each other with sufficient rapidity to sustain the increasing flux of magnetism in the iron, is manifest from the time which elapses before the electricity transmitted through the helices attains a permanent degree of intensity, and before the electro-magnet acquires its greatest amount of magnetism (45)*.

53. That the length of time which was observed to elapse, and the number of waves which required to be transmitted through the electro-helices before the current from the magneto-electric machine attained a permanent degree of intensity, and the electro-magnet acquired its greatest amount of magnetism, are dependent upon the magnitude of the waves of electricity transmitted through the electro-helices, is evident from the fact that the same degree of intensity of the current (as measured by the balance), and the same amount of magnetism in the electro-magnet, were obtained with a much smaller number of waves, and in a shorter time, from a large electromotor, than could be obtained with a much greater number of waves from a small electromotor (46). These observations will be further confirmed by experiments to be hereafter adduced.

54. The cause of the great difference between the attractive force of a permanent magnet and that of an electro-magnet excited through its agency, and also the agreement of the phenomena with the principle of the conservation of force, now become sufficiently manifest to render it unnecessary, at the present time, to institute a more rigorous comparison between the quantities of magnetism and electricity of the magneto-electric machine, and the quantities of the same forces developed in the electro-magnets (23, 33). The general conclusion which may, however, be drawn from a consideration of the preceding experiments is, that when an electro-magnet is excited through the agency of a permanent magnet, the large amount of magnetism manifested in the electro-magnet,

* Philosophical Transactions, 1846, p. 6.

simultaneously with the small amount manifested in the permanent magnet, is the constant accompaniment of, at least, a correlative amount of electricity evolved from the magneto-electric machine, either all at once, in a large quantity, or by a continuous succession of small quantities (45, 46),—the power which the metals (but more particularly iron) possess of accumulating and retaining a temporary charge of electricity, or of magnetism, or of both together (according to the mode in which these forces are viewed by physicists), giving rise to the paradoxical phenomena which form the subject of this research*.

§ 2. *On a new and powerful Generator of Dynamic Electricity.*

55. The fact that a large amount of magnetism can be developed in an electro-magnet by means of a permanent magnet of much smaller power having been established, and as from the first series of experiments (Table I.) it was shown that definite quantities of magnetism are accompanied by the evolution of proportionate quantities of dynamic electricity, and since an electro-magnet, when excited by means of a voltaic battery, possesses all the properties of a permanent magnet, it appeared reasonable to suppose that a large electro-magnet excited by means of a small magneto-electric machine could, by suitable arrangements, be made instrumental in evolving a proportionately large quantity of dynamic electricity, notwithstanding the pulsatory character of the electricity transmitted through the wires surrounding the electro-magnet.

56. Two magnet-cylinders, of similar construction to the one already described (9)

* Since the publication of the abstract of this paper in the Proceedings of the Royal Society, my attention has been directed to several accounts of experiments in which electro-magnets, excited by means of magneto-electric machines, have been made to sustain considerable weights. The most important of these accounts which have come under my notice, is one contained in SILLIMAN's Journal of Science for 1845, vol. xlviii. p. 393, in which it is stated that Dr. PAGE, by means of a magneto-electric machine, made an electro-magnet sustain a weight of 1000 lbs.

Another account to which I have been referred, is contained in a Treatise on the Electric Telegraph, by M. l'Abbé MOIGNO, Paris, 1849, in which it is stated (page 15, p. 72 in the second edition) that the Abbés MOIGNO and RAILLARD, by means of a small machine, made an electro-magnet sustain a weight of 600 kilogrammes.

In neither of these accounts, however, does any direct comparison appear to have been made between the sustaining-power of the permanent and the electro-magnets, as no mention is therein made of the sustaining-power of the permanent magnets, nor are they (the permanent magnets) specifically mentioned.

In a brief notice of my experiments which appeared in 'Les Mondes' of September 6th, 1866, of which Journal M. l'Abbé MOIGNO is the editor, he gives what professes to be a quotation from his 'Traité de Télégraphie Électrique,' in which he has introduced a statement specifying the sustaining-power of the permanent magnets used in his experiments, although no such statement is to be found in the treatise from which the quotation is taken.

Another discrepancy with reference to the account of MOIGNO's experiments also occurs in an article on "WILDE's Magneto-electric Machine," in the Quarterly Journal of Science for October 1866, in which the writer would seem to have mistaken a small electro-magnet (used only as an adjunct to a magneto-electric machine, and which MOIGNO states would only support a few grammes) for the permanent magnets which excited the electro-magnet; and from this error it is made to appear that the permanent magnets used by MOIGNO would only sustain a few grammes.

(figs. 1, 2, 3, 9), were therefore made, having a bore of $2\frac{1}{2}$ inches and a length of $12\frac{1}{2}$ inches, or five times the diameter of the bore.

57. As frequent mention will have to be made of the different-sized machines employed in these investigations, they will in future be distinguished by their calibre, or the diameter of the bore of the magnet-cylinder.

58. Each cylinder was fitted with pillars, cross-heads, and an armature similar to those already described (9, 10) (figs. 3, 6). Around each armature was coiled an insulated strand of copper wires 67 feet in length and 0·15 of an inch in diameter, the extremities of which were respectively connected with the two halves of a commutator fixed on the axis of each armature (10). Upon one of the magnet-cylinders (fig. 1) sixteen permanent magnets, of the form shown in the figure, 12 inches in length, were fixed. Each of the magnets weighed 3 lbs., and would sustain a weight of 20 lbs.

59. To the sides of the other magnet-cylinder, an end view of which is shown in fig. 9, two rectangular pieces of boiler plate, O, O, $12\frac{1}{2}$ inches long, 9 inches wide, and $\frac{3}{8}$ of an inch thick, were bolted parallel with each other and between the iron packings P, P, P′, P′. The upper extremities of these plates were united by means of a hollow bridge, Q, to which they were bolted, along with iron packings similar to those on their lower extremities. The bridge was made of two thicknesses of the same boiler-plate iron as that of which the sides were made; and for the purpose of ensuring good contact, its edges, as well as those parts of the sides of the rectangular plates in contact with them and with the magnet-cylinder, were planed to a true surface. An insulated strand of copper wires, 350 feet in length, and of the same diameter as that on the armature (58), was coiled round each of the rectangular iron plates in a direction parallel with the axis of the magnet-cylinder. The two coils were united so as to form a single circuit 700 feet in length, the free ends of which were furnished with suitable terminal screws, for the purpose of connecting them with the wires from the $2\frac{1}{2}$-inch magneto-electric machine. A perspective view of this machine is shown in fig. 10, but on a much larger scale than the magneto-electric machine which is placed on the top of it. The $2\frac{1}{2}$-inch magneto-electric and electro-magnetic machines were placed side by side upon a strong wooden base, and their armatures were driven simultaneously from the same driving shaft, at an equal velocity of about 2500 revolutions per minute.

60. Experiments were then made for the purpose of comparing the quantities of electricity evolved from the magneto-electric and electro-magnetic machines, as measured, approximately, by their heating effects. When the alternating waves from the magneto-electric machine were transmitted through a piece of No. 20 iron wire, 0·04 of an inch in diameter, a length of 3 inches of this wire was raised to a red heat.

61. The direct current (15) from the magneto-electric machine was then transmitted through the coils surrounding the iron plates O, O, which being united by the bridge Q, formed a powerful electro-magnet similar in construction to that invented by JOULE*, and having for its poles the two sides of the magnet-cylinder. When the alter-

* Philosophical Magazine, S. 4. vol. iii. p. 32.

nating waves from this electro-magnetic machine were transmitted through the same-sized iron wire as was used in the preceding experiment, 8 inches of it were melted, and a length of 24 inches was raised to a red heat.

62. A comparison of the heating effects of the two machines, as found by these experiments, brings out the important fact, that a much greater amount of electricity is evolved from the electro-magnetic machine than is evolved simultaneously from the magneto-electric machine. Moreover, considering the smallness of the quantity of iron of which the armature was made (only five pounds), and of the copper wire surrounding it, the weight of which was only $3\frac{1}{2}$ pounds, the heating effects of the electro-magnetic machine are very remarkable. One of the most energetic generators of dynamic electricity is that invented by GROVE, and it was found from experiments made with four new cells of this battery, the platina plates of which were $6 \times 3\frac{1}{2}$ inches, with double zinc plates well amalgamated, and charged with concentrated nitric acid and a strong solution of sulphuric acid, that ten cells of this powerful arrangement would be required in order to produce the same heating effects as those produced by the electro-magnetic machine.

63. For the purpose of ascertaining in what ratio the power of the electro-magnetic machine would be increased by an enlargement of its dimensions, a machine was constructed double the size of the one described (59), but of precisely the same proportions. The bore of the cylinder was 5 inches in diameter, and its length 25 inches. The copper wire strand surrounding the electro-magnet was 1170 feet in length, and weighed about 390 lbs. The armature of this machine was coiled with an insulated copper strand 84 feet in length, the weight of which was about 28 lbs.

64. When the electro-magnet of the 5-inch machine was excited by the $2\frac{1}{2}$-inch magneto-electric machine, the armature of the 5-inch machine being driven at about 2000 revolutions per minute, the electricity from it melted 15 inches of No. 15 iron wire 0·075 of an inch in diameter. Now it was found that a piece of No. 15 iron wire 15 inches in length, was about seven times the weight of 8 inches of the wire melted by the $2\frac{1}{2}$-inch electro-magnetic machine (61); and as the 5-inch machine was about eight times the weight of the $2\frac{1}{2}$-inch electro-magnetic machine, the increase of power of the 5-inch machine, as measured by its heating effects, appears to me to be nearly in direct proportion to the increase of its cubical dimensions, after allowance has been made for the diminished speed at which the armature was driven, together with the small increase of power which might have been obtained had the electro-magnet been excited by a more powerful magneto-electric machine.

65. For the purpose of learning to what extent the power of the electro-magnetic machine might be increased by an exaltation of the magnetism of the electro-magnet, without changing the speed at which the armature was driven, the electro-magnet of the 5-inch machine was excited by the direct current from the $2\frac{1}{2}$-inch electro-magnetic machine (59), the latter being in its turn excited by the $2\frac{1}{2}$-inch magneto-electric machine (58). On making the experiment, it was found that although the magnetism of the

electro-magnet (63) was considerably increased, yet this increase was only accompanied by a very small additional quantity of electricity from the armature; thus showing that the full power of the 5-inch machine had been very nearly attained, when its electro-magnet was excited by the $2\frac{1}{2}$-inch magneto-electric machine alone.

66. Having found that an increase in the dimensions of the electro-magnetic machine was accompanied by a proportionate and satisfactory increase of the magnetic and electric forces, a 10-inch electro-magnetic machine was constructed; and as its calorific and illuminating powers are very remarkable, some particulars respecting the machine, together with a few experiments made with it, may perhaps be found to possess some interest, especially for those physicists who are engaged in determining the quantitative relations existing between the various forces as manifested to the senses.

67. In describing the different parts of the machine, reference will still be made to figures 1–9, which have been drawn to a proportionate scale. A perspective view of the machine complete is shown in fig. 10. Each side of the electro-magnet O, O, fig. 9, is made of a plate of rolled iron 48 inches in length, 39 inches wide, and $1\frac{1}{2}$ inch in thickness. The wrought-iron bars P, P, P′, P′, bolted to the upper and lower extremities of the plates, are 6 inches wide and 2 inches thick. These bars are somewhat longer than the width of the plates, and are secured to the sides of the magnet-cylinder, with the plates between them, by means of iron bolts 1 inch in diameter. The bridge Q extends the whole length of the bars P′, P′, and is made of two plates of rolled iron 43 inches long, 16 inches wide, and $1\frac{1}{2}$ inch thick, separated from each other by an iron packing 3 inches in thickness, which makes the entire depth of the bridge equal to the width of the bars P′, P′. The bridge is fixed between the side plates by means of long iron bolts 1 inch in diameter, extending from one side of the magnet to the other, as shown in the figure. All the component parts of the electro-magnet which required to be fitted together were planed to a true surface, for the purpose of ensuring intimate ferruginous contact throughout the entire mass. The total weight of the iron of the electro-magnet, exclusive of the magnet-cylinder, is a little more than 1·5 ton.

68. Each side of the electro-magnet was coiled with an insulated conductor, consisting of a bundle of thirteen No. 11 copper wires, each 0·125 of an inch in diameter, laid parallel with each other, and bound together with a double covering of linen tape, after the manner adopted by Joule in the construction of his electro-magnets*. The length of conductor coiled round each side of the electro-magnet is 2400 feet, and the outer extremities of the coils are coupled up so as to form a continuous circuit 4800 feet in length. The inner extremities of the coils terminate in two insulated metal studs fixed upon the wooden top of the machine (fig. 10). The total weight of the two coils is 1·3 ton.

69. The magnet-cylinder consists of two masses of cast iron 50 inches in length, separated from each other by an interval of 5 inches, by means of blocks of brass placed at intervals along the top and bottom of the cylinder. All the flat surfaces of the latter,

* Annals of Electricity, vol. v. p. 472.

as well as those of the brass blocks in contact with them, are truly planed, and the several parts of the cylinder are bolted together at the top and bottom by means of twelve copper bolts 1 inch in diameter. The bore of the magnet-cylinder is 10 inches, and its weight, when fitted up with iron pillars and brass cross-heads, is 1·1 ton.

70. The machine is furnished with two armatures, one for the production of "intensity," and the other for the production of "quantity" effects. These armatures are made of cast iron, and are precisely alike in dimensions, as they were cast from the same pattern. The thickness of the rib G, fig. 5, uniting the segmental sides of the armatures is 1·75 inch, and the latter are turned one-eighth of an inch less in diameter than the bore of the magnet-cylinder. A pulley, 10 inches in diameter, is keyed upon one end of each armature, and upon the other end is fixed a commutator, by means of which the waves of electricity from the armature can be taken, either in the same or in alternate directions as required (15, 16).

71. The intensity armature is coiled with an insulated conductor consisting of a bundle of thirteen No. 11 copper wires, each 0·125 of an inch in diameter, the same as that coiled round the sides of the electro-magnet (68). The conductor is 376 feet in length and weighs 232 lbs., and is covered with a casing of wood extending the entire length of the armature, for the purpose of protecting it from external injury. Strong bands of sheet brass, 1 inch in width, encircle the armature at intervals of 6 inches, for the purpose of keeping the casing and the convolutions of the conductor in position during their rapid revolution (11). The total weight of this armature with all its fittings is 0·3 of a ton.

72. The quantity armature is enveloped with the folds of an insulated conductor, consisting of four plates of copper, each 67 feet in length, 6 inches in width, and one-sixteenth of an inch in thickness. These plates are superposed in metallic contact with each other, so as to form a single copper plate one-quarter of an inch in thickness, 67 feet in length, and nearly wide enough to occupy the entire width between the segmental sides of the armature. This division of the conductor into four plates was made for the greater convenience of bending it round the armature. The inner extremity of the conductor is held in intimate contact with the body of the armature by means of flat-headed screws; and the convolutions are insulated from one another by placing between them a band of thick cotton and india-rubber fabric, of the same length and width as the laminated conductor; and the edges of the latter are insulated from the sides of the armature by means of thin pieces of wood. The outer extremity of the conductor is terminated by a thick copper stud which connects it with the insulated half of the commutator fixed on the armature axis; and the convolutions are retained in position, by means of bands, in the same manner as those of the intensity armature (11, 71). The weight of the laminated copper conductor is 344 lbs., and the total weight of the armature is 0·35 of a ton.

73. The armatures were accurately balanced before being placed in the magnet-cylinder, for the purpose of avoiding the excessive vibrations which were produced when they revolved at high velocities without being balanced. By means of a small carriage, the

quantity and intensity armatures could easily be withdrawn from the magnet-cylinder, and interchanged, when required, in the course of a few minutes, the cross-head at the driving end of the machine being readily removeable for that purpose.

74. Though the total weight of the 10-inch electro-magnetic machine complete is very considerable, being nearly 4·5 tons, yet its dimensions are comparatively small, since the entire length of the machine, including the brass cross-heads, is only 80 inches, its width 24 inches, and its height 60 inches.

75. Experiments were first made with the machine, for the purpose of testing its power when the large electro-magnet was excited by magneto-electric and electro-magnetic machines of various sizes. The 10-inch machine, as well as the machines used for exciting it, were all driven from the same countershaft by means of pulleys of suitable dimensions. The intensity and quantity armatures (71, 72) were driven at a uniform velocity of about 1500 revolutions per minute, by means of a broad leather belt of the strongest description. The springs for taking the electricity from the 10-inch machine were connected, by means of large copper conductors, with two insulated plates of copper let into the under side of an experimental table. On the upper side of this table were two moveable brass studs, sliding in good contact with the copper plates, and forming the polar terminals of the machine.

76. The quantity armature was first placed in the cylinder, and the springs were so arranged as to take the alternating currents of electricity from the polar terminals (16). The direct current from the small magneto-electric machine, having on its cylinder six permanent magnets, such as were used in the first series of experiments (12), was then transmitted through the coils of the electro-magnet of the 5-inch electro-magnetic machine (63); and the direct current from the latter was simultaneously, and in like manner, transmitted through the coils of the electro-magnet of the 10-inch machine.

77. This combination of the machines, when in full action, was attended by the development of an amount of magnetic force in the large electro-magnet far exceeding anything which has hitherto been produced, together with the evolution of a quantity of dynamic electricity from the armature so enormous as to melt pieces of cylindrical iron rod 15 inches in length, and fully one-quarter of an inch in diameter. With the same arrangement, the electricity from the quantity armature also melted 15 inches of No. 11 copper wire 0·125 of an inch in diameter.

78. When the intensity armature (71) was placed in the cylinder, the combination of the machines remaining the same as in the preceding experiments (76), the alternating current from the armature melted 7 feet of No. 16 iron wire 0·065 of an inch in diameter, and made a length of 21 feet of the same wire red-hot.

79. The illuminating power of the electricity from the intensity armature is, as might be expected, of the most splendid description. Two rods of gas-carbon, half an inch square, were placed in the carbon-holders of the beautiful apparatus for regulating the electric light, recently invented by M. FOUCAULT, behind which was fixed a parabolic reflector 20 inches in diameter, so adjusted as to cause the rays of light to diverge from

it at a considerable angle. When the electric lamp was placed at the top of a lofty building, the light evolved from it was sufficient to cast the shadows from the flames of the street-lamps a quarter of a mile distant upon the neighbouring walls. When viewed from that distance, the light was a very magnificent object to behold, the rays proceeding from the reflector having all the rich effulgence of sunshine.

80. A piece of the ordinary sensitized paper, such as is used for photographic printing, when exposed to the action of the light for twenty seconds, at a distance of 2 feet from the reflector, was darkened to the same degree as was a piece of the same sheet of paper when exposed for a period of one minute to the direct rays of the sun, at noon, on a very clear day in the month of March.

81. The extraordinary calorific and illuminating powers of the 10-inch machine are all the more remarkable from the fact that they have their origin in six small permanent magnets, weighing only 1 lb. each (12), and only capable, at most, of sustaining collectively a weight of 60 lbs.; while the electricity from the magneto-electric machine which was employed in exciting the electro-magnet was, of itself, incapable of heating to redness the shortest length of iron wire of the smallest size manufactured.

82. The production of so large an amount of electricity was only obtained (as might have been anticipated by the physicist) by a correspondingly large expenditure of mechanical force, as the machine when in full action absorbed, as nearly as could be estimated, from eight to ten horse-power. When the $2\frac{1}{2}$-inch magneto-electric machine (58) was substituted for the $1\frac{5}{8}$-inch machine, in the combination before described (76), the magnetism developed in the electro-magnet of the 10-inch machine was exalted to such a degree that, although the strong leather belt from the main shaft, used for driving the countershaft, was 6 inches in width and acted upon a pulley 10 inches in diameter, it was scarcely able to drive the machine.

83. It was, however, found, as in the case of the 5-inch electro-magnetic machine, that beyond certain limits a great augmentation of the magnetism of the electro-magnet was only attended by a small increase of electricity from the armature (65). The results of a number of experiments, in which various quantities of electricity were transmitted through the coils of the electro-magnet of the 10-inch machine, proved that when it was excited through the agency of the six permanent magnets, combined with the 5-inch machine, (76), the maximum amount of electricity from the machine, when working at a speed of 1500 revolutions per minute, had been nearly obtained.

84. It was also found that the maximum amount of power, as measured by the quantity of wire melted, was very nearly obtained from the 10-inch machine when its electro-magnet was excited by means of a 5-inch magneto-electric machine alone, instead of the combination of magneto-electric and electro-magnetic machines used for that purpose (76).

85. When the electro-magnet of the 10-inch machine was excited by means of the $2\frac{1}{2}$-inch magneto-electric machine alone (58) (as shown on the wooden top of the machine in fig. 10), about two-thirds of the maximum amount of power from the 10-inch machine was obtained.

Fig. 1.

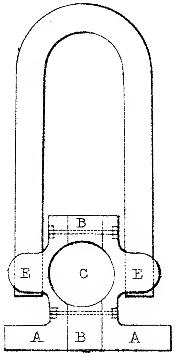

Fig. 2.

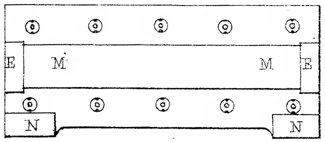

Fig. 9.

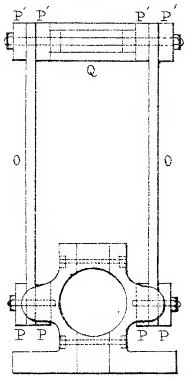

Fig. 3.

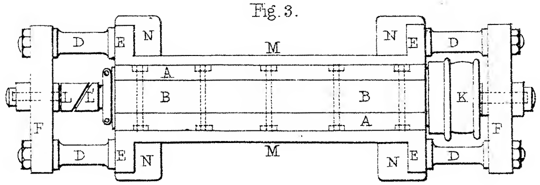

Fig. 5.

Fig. 4.

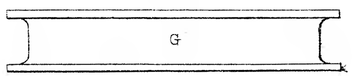

Fig. 7.

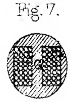

Fig. 6.

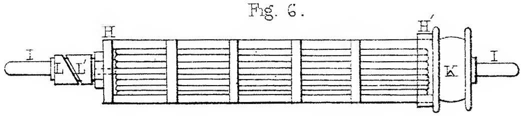

Fig. 8.

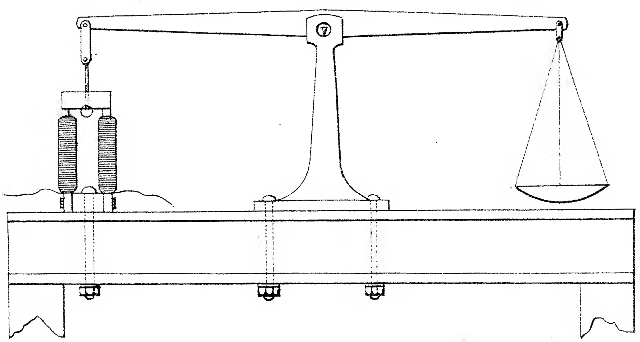

Fig. 10.